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**PROGRESS REPORT OF A RESEARCH PROGRAM
IN EXPERIMENTAL HIGH ENERGY PHYSICS**

**Task B
Progress Report
for Contract Period January 1, 1990 to December 31, 1990**

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Progress Report of a Research Program
in Experimental High Energy Physics
Task B

The Department of Physics of Brown University presents herein a report of the progress made in the experimental program during the present contract period (1 January 1990 – 31 December 1990). This work has been supported by the U.S. Department of Energy under Contract DE-AC02-76ER03130 (Task B – Experimental).

This report on the Task B program is divided as follows:

- I. Data Analysis in Progress
- II. Experimental Runs in Progress and in Preparation
- III. Associated Matters
- IV. Scientific Personnel
- V. Papers Published and in Preparation during the Preceding Year

ABSTRACT

Two prototype tracking system modules of the LVD detector have been produced by the direct-mount method and tested. The direct-mount procedure was proposed by a subgroup (mainly U.S.) of the LVD Collaboration. This method has the advantages over the previous (hood) design of a greater signal-to-noise ratio, of providing spacing between the two streamer chamber layers of each tracking plane to improve track reconstruction and angular resolution, economy and speed of production. The tests have shown very satisfactory performance, both of the mechanical aspects and of the read-out electronics which are principally Brown's responsibility. The Collaboration has agreed to proceed with production by this method.

The full boot node data acquisition computer and one tower microvax, both provided by the Brown group, have been installed in Hall A of Gran Sasso, where data acquisition development will proceed.

FNAL Experiment E782, a study of the interactions of muons from the Tevatron, using an upgraded version of the E745 hybrid system, is now running at Fermilab.

During the past year, film analysis of the 1987 run of E745, a study of the interactions of muon neutrinos, was essentially completed and a data summary tape is being produced.

Also during the past year, analysis has continued both on the data of our experiments on interactions of hadrons with protons and heavier nuclei (FNAL E565, E570, E299, E154) and on the data of SLAC experiments BC72/73/75, studying the interactions in hydrogen of 20 GeV/c photons.

I. DATA ANALYSIS IN PROGRESS

a) Muon-Neutrino Studies at Tevatron Energies Using the Tohoku One-Meter High-Resolution Bubble Chamber as Target (E745).

The second run of E745 at Tevatron II was carried out during the last previous fixed target run, from late June 1987 through February 1, 1988. A total of 364,991 conventional three-view bubble chamber pictures were obtained, with 62,744 accompanied by triggered holographic pictures. The 1987 detector layout is shown in Fig. 1a) 1.

Scanning and measuring of the film of this 1987 run has essentially been completed. Brown was responsible for scanning and measuring the Brown/FNAL/MIT portion of the film, which was carried out in the splendid Film Analysis Facility at Fermilab, now discontinued. Dr. Mukunda Aryal of Brown supervised the film analysis. Some remeasurements are being carried out at Tohoku University, and a data summary tape is being prepared.

These new data are a vital addition to the data obtained in our first run in 1985. The detector layout for that run is shown in Fig. 1a) 2. The 1985 run yielded 188,900 usable conventional three-view bubble chamber pictures, which have previously been scanned and measured.

Data analysis has been carried out and continues on this body of data. Specific topics include various investigations of particle production in neutrino-nucleus interactions at the Tevatron: Multiplicity and fragmentation; meson production; strange-particle production; EMC effect and hadron formation. The analysis effort has had lower priority during the current year than preparation for and running of E782, our study of muon interactions in an upgraded version of the E745 muon neutrino system, but will be pursued vigorously once the E782 run has ended. The film analysis for E782 will be carried out at Tohoku University as the U. S. groups have discontinued their film analysis facilities.

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FIG. 1a) 1

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Layout of 1985 E745 Detector System

b) Studies of Hadron Interactions with Hydrogen and Heavier Nuclei.

The following experiments are all in the stage of physics analysis, and many publications have already been produced from these data, as reported in previous and current progress reports.

- (1) High Statistics Study of Particle Production and Dynamics and Their Dependence on Incident Quantum Number (FNAL Experiment 570).
- (2) A Study of the Detailed Characteristics of Hadron-Nucleus Collisions using the Fermilab Spectrometer (FNAL Experiment 565).
- (3) Studies of $\pi^\pm p$, $K^+ p$ and pp Interactions at 147 GeV/c (FNAL Experiment 299) and of $\pi^- p$ Interactions at 147 GeV/c (FNAL Experiment 154) using the Proportional Wire Chamber Hybrid System at Fermilab.

The first two experiments listed above provide data for a study of the dynamics of hadron production in hydrogen and in heavy targets, using four incident hadron beams: $\pi^\pm$, K^+ and p , all at a momentum of 200 GeV/c.

The experimental run, completed in mid-1982, resulted in a total of about one million pictures which, because of the low-systematic-error nature of the experiment, continue to yield physics results of interest.

The experiments were done using as the visible target the 30-inch bubble chamber filled with hydrogen and containing near its upstream boundary thin foils of magnesium, silver and gold (two thicknesses of each to allow for correction for multiple interactions in a foil). The beam was tagged by means of Cerenkov counters in the portion of the spectrometer upstream of the target. The downstream spectrometer included CRISIS for the identification of charged secondary particles, as well as proportional wire chambers and drift chambers to record their trajectories, and a lead glass detector (FGD) for the detection of forward-going gamma rays (see Fig. 1b) 1. The experimental arrangement provides for the simultaneous detection and analysis in the same exposure, using the full power of the visible target and the spectrometer, of events produced in the hydrogen and in three heavy nuclei. Data were obtained simultaneously for all the positive beam particles and all the targets, and there was

5-A

D: drift chamber triplets P: proportional wire planes S: scintillators

BEAM-LINE COMPONENTS IN FERMILAB HYBRID SPECTROMETER FOR E565/570

FIG. 1b) 1

no change in the apparatus when a negative beam was used. The system was run in an untriggered mode, so systematic biases were minimal.

Of the approximately 1×10^6 pictures taken, about 218,000 were taken with a negative beam (mostly π^-) and the remainder with a positive beam. The positive beam composition varied somewhat during the run, and averaged approximately 49% pions, 36% protons and 15% K mesons.

Data analysis has concentrated on the study of interactions as a function of A and of incident particle, for which the bubble chamber vertex detector provides unique data. Analysis of some aspects of these interactions has been reported earlier – for example we have recently published a study of multiparticle production in the interactions of 200 GeV/c protons and π^+ and K^+ mesons with nuclei of gold, silver, and magnesium.¹ In that paper we investigated the correlations of multiplicities and dispersions with the numbers of projectile and secondary collisions in the nucleus. Here we report a study of rapidities and rapidity correlations, again emphasizing the dependence on the number of projectile collisions. Previous results on the general topic of rapidities in hadron-nucleus collisions have been reviewed by Fredricksson et al.² and by Busza and Ledoux.³ As said above, a notable feature of our experiment is that we have three different incident beam types and three different targets, thereby providing nine reactions all analyzed in an identical manner.

To obtain our data sample from the total exposure, we imposed the requirement that there be more than three charged particles in the final state, so as to compensate for different scanning biases in low-multiplicity hydrogen and plate events, and to remove elastic events. After this cut, the sample consisted of 1313 plate events and 896 hydrogen events. Table I shows the division of these events among the various beam types and targets.

For the analysis reported here, we define the rapidity in the laboratory frame as $y = 1/2 \ln[(E + P_L)/(E - P_L)]$, where E and P_L are the total laboratory energy and longitudinal momentum of the particle under consideration. (The rapidity in the hadron-nucleon center of mass frame is shifted by 3.0 units). We follow the usual practice of presenting the rapidities only of “produced-particles”, which we define

as all particles except those identified by ionization as protons. Figure Ib)2 shows normalized rapidity distributions of produced particles separately for the π^+ and p beams, and also separated by target type. The distributions are normalized to the total number of events N for each reaction, so that the abscissa at any point represents the average multiplicity of produced-particles per unit interval of rapidity. Even at the highest momenta, our resolution in rapidity is generally no worse than 0.1 units, and for the bulk of the particles the resolution is much better. Since our bin size in Figure Ib)2 is 0.5 units, resolution does not significantly influence the shapes.

The qualitative features of Figure Ib)2 can be understood by considering the effects of multiple projectile collisions. For each beam type, as the target mass A increases, the distributions shift to lower rapidities and their heights increase. As noted in our previous paper,¹ multiplicities increase linearly with the number of projectile collisions, which in turn increase with A , thereby raising the heights of the distributions. However, as the number of collisions increases, the energy of the projectile has to be shared by more particles, so that the average rapidity decreases. It may be noted that for large values of rapidity the distributions for all targets come close together and possibly even exhibit a cross-over. Because of energy conservation, the amount of particle production at high rapidities is limited. A cross-over is plausible since the projectile itself gradually loses energy by repeated collisions inside the nucleus. Finally, the proton beam does induce more projectile collisions than the π beam,¹ which accounts for the difference in heights of the rapidity distributions for those two beams for any given target. The distributions for the K beam are similar to those for the π beam, but with reduced statistical accuracy.

Additional information can be obtained by examining the ratio $R(y)$ of normalized rapidities for hadron-nucleus interactions to those for hadron-proton interactions: $R(y) = (1/N dn/dy)_{hA} / (1/N dn/dy)_{hp}$. Such plots have been published by DeMarzo et al.⁴ using streamer-chamber data on 200 GeV/c p and $\bar{p}$ interactions with Xe and Ar, and by Bailly et al.⁵ using European Hybrid Spectrometer data on 360 GeV/c proton collisions on Au and Al. In Figure Ib)3 we show $R(y)$ for our π beam on Au and Ag targets, and the corresponding plots for p and K^+ beams show similar

Fig I b) 2

Rapidity distributions of all produced-particles, normalized to the total number of events in each reaction, for (a) π^+ beam, and (b) proton beam. The rapidities are in the laboratory frame, and are shown separately for the three metal targets and for hydrogen.

FIG 1b) 3

Ratio of normalized rapidity distributions of all produced-particles for π^+ -nucleus to π^+p interactions, for (a) gold target, and (b) silver target.

features. Our statistics are intermediate between those of Refs. 4 and 5, but we have data from meson as well as proton beams, while Refs. 4 and 5 have nucleon beams only.

In the projectile fragmentation region ($y > 5$) we observe that $R(y)$ is less than one for all combinations of beams and targets. No doubt this reflects the projectile's loss of energy in repeated collisions, as was mentioned above in the discussion of cross-over in Figure 1b). In the central region ($2 < y < 4$) there is a suggestion of a plateau, with only a weak dependence on y . The height of the plateau ($R \sim 2$) is sometimes identified with the average number of wounded constituents of the beam in a number of models,⁶ such as the additive quark model. In the target fragmentation region ($y < 1$) the ratio $R(y)$ becomes much larger, because secondary collisions of recoiling nucleons inside the nucleus induce multiplication of low-momentum particles.¹ However, it is in this target region that we observe some disagreements with the results of Ref. 4. For all our beams and targets, $R(y)$ at low rapidities does not exceed a value of about 7 or 8. DeMarzo et al.⁴ reported significantly higher values, especially for p-Xe data, where they found $R(y)$ exceeding 30. Proton contamination may be a pertinent factor, since they identified protons only up to momentum 0.6 GeV/c, whereas our identification extends up to 1.2 GeV/c. We also have some disagreement, although smaller, with Bailly et al.,⁵ who reported $R(y) \sim 20$ for low rapidities for 360 GeV/c p-Au collisions. However, they did not select produced-particles in the same way as we and Ref. 4 did, instead defining "shower" particles as all those with bubble densities less than 1.3 times minimum-ionizing.

To eliminate any complication due to proton contamination, we examined rapidity ratios $R_{-}(y)$ of negative particles for π and p beams, and found that they are very similar to $R(y)$, which suggests to us that our data for $R(y)$ are not significantly affected by protons. We do find that there are many protons in the momentum range 0.6-1.2 GeV/c, so that we would expect an experiment like Ref. 4, which includes protons in that momentum range as produced particles, to exhibit higher values of $R(y)$ at low y than we do. On the other hand, Ref. 4 found that their distribution of $R_{-}(y)$ was also similar to their $R(y)$, which argues against protons as the explanation

for their high $R(y)$.

In our previous paper¹ we found that the most important quantity for describing the interaction between a hadron beam (h) and a target nucleus (A) is ν_p , the number of projectile collisions that occurred inside the nucleus. For a given reaction (hA) the average value of this quantity is $\langle \nu_p \rangle = A(\sigma_{hp}/\sigma_{hA})$,⁷ where σ_{hp} and σ_{hA} are the inelastic cross sections for hadron-proton and hadron-nucleus collisions respectively. To obtain an event-by-event estimate, we define⁸ $\nu_p(n_p) = C_{hA}\sqrt{n_p}$, where n_p is the number of "grey" protons (i.e. identified protons of momentum greater than 0.3 GeV/c) in the event. The proportionality constant C_{hA} is chosen so that the average value of $\nu_p(n_p)$ over all events of a given reaction (hA) will be equal to $\langle \nu_p \rangle$ for that reaction as given by the formula above. With this definition, we previously found that produced-particle multiplicities depend only on $\nu_p(n_p)$ and not on beam or target type separately.

In Figure Ib)4 we show the average rapidity of produced-particles as a function of ν_p . In Figure Ib)2 we noted that the rapidity distributions shifted to lower values of y as the target mass increased. We now see directly in Figure Ib)4 that the decrease in rapidity is due to increasing numbers of projectile collisions; the energy has to be shared by more and more particles as ν_p increases. Indeed, in Figure Ib)4 we observe that when plotted as a function of ν_p , the average rapidity has no target dependence. For all three beams the decrease is linear for low values of ν_p , but eventually exhibits a levelling-off. For the π and p beams, the levelling occurs at about $\nu_p = 5$, but for the K beam it seems to set in earlier. In the linear region, the slopes are (0.27 ± 0.02) , (-0.21 ± 0.02) , and (-0.30 ± 0.03) for the π , p , and K beams respectively.

DeMarzo et al⁹ have found it instructive to divide the rapidity interval into three regions, and in each one to examine R as a function of ν_p , where R is the ratio of normalized rapidity distributions for hadron-nucleus to hadron-proton collisions. For ease of comparison with Ref. 9, we have used the same definitions of the three rapidity regions: (i) the target fragmentation region, $y < 2.0$; (ii) the central production region, $2.4 < y < 3.6$; and (iii) the projectile fragmentation region, $y > 5.0$. (De-

Fig Ib) 4

Average rapidity of all produced-particles as a function of the number of projectile collisions, for (a) π^+ beam, (b) p beam, and (c) K^+ beam. The number of collisions was estimated event-by-event from the grey proton multiplicity.

Marzo et al. deliberately left gaps between the regions so as to eliminate transition effects). From Figure Ib)3 and similar plots for p and K^+ beams, it is clear that these definitions are suitable for our data as well. We have fewer events than Ref. 9, but we do have meson as well as proton beams, whereas Ref. 9 reported proton beam data only.

Figure Ib)5 shows R as a function of ν_p in the target fragmentation region. In agreement with Ref. 9 we observe a linear rise with no target dependence. There is not much beam dependence either; for the π , p , and K beams respectively the slopes are (1.7 ± 0.1) , (1.3 ± 0.1) , and (1.6 ± 0.2) .

Figure Ib)6 is a similar plot for the central region. Here we observe a much gentler increase of R with ν_p . This general behavior is expected in a number of models⁶ and is qualitatively in agreement with Ref. 9. However, the detailed behavior shows some discrepancies with Ref. 9. Kerman, Matsui, and Svetitsky¹⁰ have shown that a color flux-tube model predicts $R = \sqrt{\nu_p}$ (at least for proton-beam events) and that this form gives a good description of the data of Ref. 9. Li and Young¹¹ have shown that their partition-temperature model also fits the same data. In Figure Ib)6 we have included the curve $R = \sqrt{\nu_p}$ for comparison, and we see that our points consistently seem to lie above it, especially for the proton beam. This result does not depend sensitively on the exact definition of the central region.

Our statistical errors are greatest in the projectile fragmentation region. A plot of R vs ν_p in this region shows no evidence for target dependence, and the data for each beam type exhibit a slow decline which probably reflects the projectile's loss of energy as more collisions occur, which has been discussed above.

We have noted previously that we can identify protons up to a momentum of 1.2 GeV/c. To avoid the problem of proton contamination in the central region, we have calculated R_- , the ratio of normalized rapidity distributions of negative particles for hadron-nucleus to hadron-proton events. The data are quite similar to Figure Ib)6, and suggest that proton contamination is not a significant influence on the trend.

Hadron-proton interactions at moderate energies have long been known to exhibit short-range rapidity correlations. However, at very high energies ($\sqrt{s} = 540$ GeV)

Fig Ib) 5

Ratio of normalized rapidity distributions in the target fragmentation region for hadron-nucleus to hadron-proton interactions, for (a) π^+ beam, (b) p beam, and (c) K^+ beam, shown as a function of the number of projectile collisions. The lines represent linear fits to the data, and the slopes are given in the text.

Fig I b) 6

Ratio of normalized rapidity distributions in the central region for hadron-nucleus to hadron-proton interactions, for (a) π^+ beam, (b) p beam, and (c) K^+ beam, shown as a function of the number of projectile collisions. The dashed lines represent the curve $R = \sqrt{\nu_p}$, which was found to describe the data of Ref. 9.

the UA5 experiment at CERN has reported¹² long-range correlations in particle rapidities. Capella and Tran Thanh Van¹³ have noted that multiple inelastic scattering may be the mechanism producing these long-range correlations, in which case hadron-nucleus interactions should exhibit the phenomenon even at more moderate energies. Using the multichain dual parton model, Capella and Tran Thanh Van have determined that it is essential to select rapidity intervals judiciously in order to observe long-range correlations. For 200 GeV/c proton-nucleus collisions, they have predicted correlations between multiplicities in a “forward” region defined by $y = 3.25$ to 4.25 , and a “backward” region defined by $y = 0.75$ to 1.75 . Derado et al.¹⁴ have tested this prediction using the streamer chamber data of Ref. 9. They have performed fits to their data of the form $\langle N_B \rangle = a + bN_F$, where N_F is the charged multiplicity in the forward region as defined above, and $\langle N_B \rangle$ is the corresponding average charged multiplicity in the backward region. For the slope b they obtained (-0.01 ± 0.01) for $p - p$ data, and (0.41 ± 0.04) for pp -Xe data, thereby confirming the prediction of long-range correlations in hadron-nucleus interactions.

We have selected the same rapidity intervals for our investigation of possible long-range correlations. In Figure 1b) we show the correlation between $\langle N_B \rangle$ and N_F for our π^+p and π^+Au data. As expected, the hydrogen data show no evidence for any correlation, and the linear fit produces a slope of (-0.03 ± 0.04) . By contrast, the gold events do exhibit clear correlation, with a slope of (0.40 ± 0.12) . Table II gives the slopes for all such fits for our π^+ and proton beam interactions on hydrogen and on the three metal plates. For both beams, we find no correlation for hydrogen and significant correlation for gold and silver. (The statistics do not allow a meaningful result for the magnesium target or for the K beam).

We have attempted an additional test of Capella and Tran Thanh Van’s suggestion that the long-range correlations are a consequence of multiple inelastic scattering. For each beam we have combined the data for all three metal plate targets, and then divided the events into two categories: those with and without grey protons. Events with $n_p = 0$ can be expected¹ to be a fairly pure sample of events in which only one projectile collision occurred, while events with $n_p > 0$ should mostly consist of events

Fig 1b) 7

Average charged multiplicity in the rapidity region (0.75, 1.75) as a function of charged multiplicity in the region (3.25, 4.25), for $\pi^+ \text{p}$ and $\pi^+ \text{-Au}$ interactions. The lines represent linear fits to the data, and their slopes (see Table II) are a measure of long-range rapidity correlations.

with multiple collisions. In Table II we give the slope parameters for these samples.

For both beams we find that the events with $n_p = 0$ have slopes consistent with zero, while the events with $n_p > 0$ have clearly significant nonzero slopes. Therefore our data do corroborate the hypothesis of Capella and Thran Thanh Van.

TABLE Ib)I
Number of Events in Each Data Sample

Target	π^+ beam	p beam	K^+ beam
Au	230	181	97
Ag	259	255	85
Mg	80	101	25
H	326	359	211

TABLE Ib)II
Slope Parameter b for long-range correlations, where $\langle N_B \rangle = a + bN_F$

Target	π^+ beam	p beam
H	-0.03 ± 0.04	-0.02 ± 0.05
Mg	0.02 ± 0.28	0.25 ± 0.21
Ag	0.40 ± 0.09	0.39 ± 0.09
Au	0.40 ± 0.12	0.55 ± 0.15
Events with $n_p = 0$	-0.04 ± 0.09	-0.12 ± 0.09
Events with $n_p > 0$	0.40 ± 0.09	0.55 ± 0.10

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c) Studies of γp Interactions at 20 GV/c Using the SLAC Hybrid Facility (SLAC Experiments BC72/73 and BC75)

Vector meson studies have continued using the data of these experiments. Most recently, the production of the negative 3π state produced in association with $\Delta^{++}(1232)$ has been examined, for the reaction $\gamma p \rightarrow \Delta^{++}\pi^+\pi^-\pi^-$. The data show no positive evidence of an $a_1(1260)$ signal, but do show an enhancement corresponding in mass and width to the $a_2(1320)$. The presence of a broad a_1 background underlying and extending above and below the a_2 peak cannot be excluded, but it is also possible that the background is non resonant. A report on this work has just been published (See Section V). Evidence of an isovector 3π state at $\sim 1775 MeV/c^2$ has also been observed, and is being further studied.

A report (Section V) has been prepared on a search in γp interactions at $20 MeV/c$ for a short-lived axion which mixes with neutral pions and decays to e^+e^- pairs, described in an earlier progress report. The signal searched for was an excess of e^+e^- pairs relative to the number of expected photon conversions. No measurable excess of e^+e^- pairs was observed; limits have been placed on the allowed range of the π^0 coupling as a function of the assumed axion mass and lifetime.

II. EXPERIMENTAL RUNS IN PROGRESS AND IN PREPARATION

a) Muon Interactions in a Hybrid System with the Tohokn High Resolution Bubble Chamber

This experiment began test running during the spring of 1990, and is now in full production. The system is operating well and about 150,000 pictures have so far been obtained, of a total expected of about 350,000. The detector system includes the Tohoku Bubble Chamber as the visible target, as in the Muon Neutrino experiment, E745; the counter system has been substantially upgraded from E745, as shown in Figure IIa)1.

The Brown hodoscopes are once more being used in the detector. Besides bringing these back into operation (not a difficult task as they seem to be indestructable!), Brown's main responsibility has been the software for the data acquisition system and the off-line monitoring system. The on-line system of course records all the electronic data and allows monitoring of many parameters by histogramming them; the off-line system allows us to trace tracks through the detector from hits in the various counters and thus to check the over all performance of the counter system:

There were considerable changes from the E745 layout in the counter portion of the detector: E745 included scintillators, proportional wire chambers (PWC), drift chambers(DC) and limited streamer chambers (LSC). In E782, all the above except the LSC are being used; however the number of PWC planes has increased from 13 to 22, the number of DC planes has been increased from 10 to 34, and the number of scintillation counters has also been increased. Mukunda Aryal has carried out the necessary changes in both the off-line monitoring software and the on-line data acquisition and is responsible for this operation. He has also helped to bring up the hardware of the detector system, and is participating full time in the current run. He has been carrying a heavy responsibility in this experiment.

The physics aims of this experiment are summarized below:

1. Comparison of muon and muon neutrino interactions: We are using the same detector for muon and neutrino interactions, so the muon-interaction data are directly comparable with the neutrino interaction results in approximately the same energy region. The kinematics is the same in both interactions and the intermediate quark states are very similar. Systematic errors will be very low. Figs IIa) 1(a)-(c) show the distributions of Q^2, μ and W obtained in the E745 1985 run. The scale under (c) shows the W_{max} for each P_μ . A muon beam of 300 GeV/c momentum will yield data which can be compared with the E745 data.

2. This experiment will cover a wide range of $Q^2, Q^2 \geq 0$ because of the triggering method which is used. Production of vector mesons, strange particles and charm particles will be studied over the whole range from the hadron-like to point-like regions of virtual photons. Direct observation of decays in space will give us a clean sample of V^0 and charm particles. There have been extensive indirect studies¹ of these processes but ours will be direct. Production of meson-baryon pairs in strange and charm events will also be an interesting subject.

3. Nuclear effect.²

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(a)

(b)

(c)

Q^2 , ν , W distributions.

986 $\nu\mu$ CC events from E745 '85 run.

FIG. IIa) 1

17-A

b) High Energy Physics and Astrophysics Underground; Large Volume Detector at the Gran Sasso Laboratory

The major purpose of this experiment is to study muons and neutrinos from astrophysical sources. Such studies contribute to our understanding of these sources, while at the same time they provide information on particle properties and interactions at energies beyond the scope of accelerators. The physics aims will be described in some detail in the accompanying proposal.

The detector which we have designed and begun to build, LVD or Large Volume Detector, consists of a large volume of liquid scintillator divided into modules surrounded by planes of limited streamer chambers (LST's). An overview of the detector is shown in Figure IIb)1, and a summary of detector characteristics is shown in Table IIb)I. The streamer chambers form an omni-directional tracking system with high spatial and angular resolution for charged particles, while the scintillators provide good energy resolution and sensitivity to $\nu(\bar{\nu})$ interactions. The large size of LVD coupled with its relatively fine granularity, sensitive tracking and energy resolution, give this detector the ability to perform some definitive measurements in high energy physics and astrophysics. Brown's major responsibilities in this experiment are in the read out electronics for the LST's, and in data acquisition.

We have had major progress this year, constructing the first two tracking modules (portatanks with streamer tubes) of the LVD system. In order to increase the size of the signal to noise ratio, and also to enhance the tracking information by introducing a 5-cm spacer between the two layers of each streamer tube plane,^{1,2} we employed the direct mount technique, first proposed by I. Pless.³ This is a method of constructing the tracking system by gluing layers of limited streamer chambers with their read-out strips directly to the portatanks which will contain the liquid scintillation counters. This represents a departure from the original design, which had the counters in trays on separate panels which were then to be mounted around the portatanks. The implementation of the new method described below has proved to be easier than envisaged and to exceed expectations in performance.

18-A

FIG. IIb) 1

TABLE IIb)I

The Main Characteristics of LVD	
Area	2,332 M ²
Geom. Acceptance	~ 7,0000 M ² . St
Length	40 meters
Width	13.2 meters
Height	12 meters
Volume of Scintillator	2,280 (meters) ³
Mass of Scintillator	1,800 tons
Mass of Steel	1,800 tons
Number Tracking Channels	100,000
Number Streamer Tubes	20,000
Number of Phototubes	6,400
Analogue Channels	12,800
Tracking Spatial Resolution	2 cm
Energy Resolution	~ 20% (contained events)

A perspective view of an LVD portatank is shown in Fig.II b)2. It is 6.3 m long, 2.0 m wide and 1.0 m high. (About half the portatanks will be 2.5 m wide) The horizontal and vertical tracking planes of the LVD detector are built out of layers of streamer chambers fastened to the base and one vertical side of the portatanks. To each portatank are attached two such layers separated by a 5.0 cm spacer as shown in Fig II b)2. The relevance of the spacer for LVD track reconstruction and its usefulness for various LVD physics topics are discussed in Ref. 1 and Ref. 2.

Each horizontal layer of the 2 m-wide portatank consists of 25 streamer chambers, 6.3 m long and 8.0 cm wide and each vertical layer is made up of 12 streamer chambers of the same dimensions. The coordinate positions perpendicular to the chamber wires are read out by 4.0-cm-wide strips, 6.3 m long. These are labelled as X-strips. The coordinate positions parallel to the chamber wires are also read out by 4.0 cm wide strips, labelled Y-strips. The arrangement of X and Y-strips on either sides of the streamer chambers for both layers, separated by the spacer, is shown in the enlarged view of the layer sections in Fig.II b)2. It is apparent from this diagram that the Y strips extend continuously over both the horizontal and vertical layers of chambers. For the 4.0 cm wide strips, this configuration gives rise to 50 X readout strips for each horizontal layer, 24 X readout strips for the vertical layer and 152 Y readout strips that extend over both horizontal and vertical layers. Thus a complete 2 m-wide portatank with two layers of tracking chambers has a total of $2 \times (50 + 24 + 152) = 452$ channels.

Obviously, the direct mount technique requires strength and permanence of the glue employed, as well as proper techniques of use and assembly. After testing various glues, and construction of a full scale mockup at MIT,⁴ the Direct Mount Group (MIT, Brown, Indiana, Northeastern, Bologna, Torino and Beijing) considered that we were prepared to proceed to the construction of actual portatank prototypes: Two direct-mount portatanks, one 2.0 m wide and one 2.5 m wide, were built at Gran Sasso between March and May 1990. The glue used was Versilok 201. This dual component acrylic glue has been used by the petroleum, shipping, and electronics industries for over ten years. The glue bond strength is 48,000 times greater than is needed, hence

VIEW OF PORTATANK, WITH TRACKING SYSTEM LAYER DETAIL

FIG II b) 2

20-A

structural failure of the counter material will occur before the glue bond yields. A single portatank can be assembled in a little over two work days. A damaged streamer tube can be replaced in less than one hour.

We have tested the performance of the direct-mount tracking system under a variety of circumstances and after subjecting the assembly to strains more severe than expected in the actual construction and installation of the portatanks, by using the LST read out electronics designed for the experiment.⁵ In short, we consider that the direct-mount system is a proven and viable method of construction and are prepared to proceed with construction of a full tower by this method.

A block diagram of the read-out electronics is shown in Fig. II b)3. Each SGS card⁶ can be connected to 32 LST read-out strips – 16 SGS cards are mounted on each portatank. The two layers of LST's are connected to separate SGS cards (Fig. II b)4): There are 4 SGS cards connected to the horizontal X strips, 2 SGS cards connected to the vertical X strips, and 10 SGS cards connected to the Y strips. Triggers can be formed from combinations of hits in the horizontal or vertical X layers, using the DIGOR signals from the appropriate SGS cards. When a Trigger signal is received in the system, the data on the SGS card are frozen. A controller, the streamer-tube read-out controller (STROC)⁷ collects the data, codes it efficiently, and transmits the data to the computer. The flow of signals between the SGS cards and the controller is illustrated in Fig. II b)5. In the experimental system, the data from each tower will be gathered via a STARBURST INTERFACE and a diskless tower microvax. The tower microvaxes will be connected in a local area vax cluster (LAVC) by ethernet cable to a full boot node microvax. (In our present test system, the CAMAC is connected directly to an IBM PC compatible computer.)

The computer can reset, read out or write in the controller. The cards can be connected in "chains" of up to 32, so each chain could be up to 1024 elements long. However, our chains are 16 cards long, one chain per portatank. These elements are read out serially, and we use shorter chains for speed. Each controller can accommodate up to eight chains – these are read out in parallel into eight independent block memories. Thus in our application each controller board handles over 4000 counter

STREAMER TUBE ELECTRONICS
BLOCK DIAGRAM

FIG II b) 3

21-A

INFN STREAMER TUBE INTERFACE - SGS 32/NN

Board Functional Block Diagram

LEGEND

1 - 32 signal inputs
 DIGOR digital OR of the
 one-shot outputs
 SRCP shift register clock
 input
 positive edge of logic
 input causes data to
 advance through shift
 register

SR LOAD shift register load input
 causes transfer of the
 logic status of comparato
 to the shift register

SRIN } daisy chain connections
 SROUT }

V_{TH} threshold voltage input

Fig II b) 5

21-C

channels. In the eight block memories, each counter channel is represented by its chain number (1-8) and its location on the chain, corresponding to the matrix array shown in Fig. II b) 6. Clearly, for any given trigger this array is likely to contain many zeros, and it is essential to compress the information. This is done in the controller by using a cluster code to eliminate zeros while retaining position information. Clusters of adjacent struck counter channels are located and identified, and a 16-bit word is written out for each cluster, as follows:

Encoded Information

Bits 0-2: Cluster Size (1-7)

Bits 3-5: Chain Number (0-7)

Bits 6-15: Coordinate position (1-dimensional) of the last channel in the cluster, along the chain of SGS card channels. (1-1024 Max, 1-512 in our case)

Data from different chains are demarcated by a chain END WORD, similar in representation to a data word. The END word representation is given below.

Bits 0-2: Cluster Size (always 0)

Bits 3-5: Chain Number (0-7)

Bits 6-15: A pattern that can be set by switches in the STROC to identify the Controller ID.

Each chain will eventually also have a shift register-test pattern, which will be read out through the whole shift register to check its operation on each trigger.

For our prototype module tests we are using an on-line data collection and analysis facility, developed by Asoka DeSilva. This is a menu-driven, user friendly, multitask data acquisition system employing an IBM PC compatible, with hard and floppy disk drives and screen printout facility, connected to a DSP Crate Controller. The software is written in Turbo Pascal, because of its reputed speed. The data acquisition system can be used to collect and store data on the computer hard disk and/or examine the performance of the portatank streamer chamber layers in real time by viewing

HIT ADDRESS MATRIX

# CHAN	# SENSOR													SUM
	1	2	3	4	5	6	7	8	9	10	11	12	13	1024
1	0	0	0	0	0									
2	0	⊕	⊕	0	0									
3	0	0	0	0	0									
4	0	0	0	0	⊕									
5	0	0	0	⊕	0									
6	0	0	0	0	0									
7														
8														
9														
10														
11														
<hr/>														
N	0	0	0	0										

A. GAVESTRO, M. VASCON, REF. 7

FIG. IIb) 6

22-A

updates of displays on the screen. This data acquisition system provides the following facilities.

- i) Facility to perform runs of fixed duration.
- ii) Facility to perform runs for a prefixed number of triggers.
- iii) Facility to examine single events, one at a time.
- iv) Facility to perform runs for an indefinite period of time.
- v) Facility to record and display the counts in all channels in histogram form, for any run.
- vi) Averages and standard deviations can be calculated on line for any predefined group of channels.
- vii) Facility to perform a plateau run and display the plateau curves for any strip channel.
- viii) A home made data base to store and retrieve all relevant parameters such as threshold settings, chamber id numbers and chamber location.
- ix) Geometry of each event can be reconstructed.
- x) The Kermit software package can be used to transfer data from this computer to a Vax computer over the ethernet for extensive data analysis.

The system is very flexible - the user can specify the contents of any run, and can include histograms, raw data, comments. Asoka is preparing a report on this system.

The tests carried out on the prototype modules employed the ambient radioactivity of the laboratory to measure individual chamber plateaus and the total portatank counting rate, and also to study the uniformity of the counting rate among the strip channels. We also determined the cluster-size distribution for both X and Y-strips as a function of the chamber high voltage. Measurements were made before and after the rotation of the portatank to ensure that the performance of the system is unaffected by the portatank orientation, and with the portatank loaded with liquid scintillator tanks and unloaded, to see effects of loading stress on the tracking system. No

significant changes in performance were found. An account of the performance tests follows:

(a) Streamer Chamber Plateaus

After the completion of the gluing of both tracking layers and the installation of the high voltage, gas and SGS card readout chain, individual chamber (tube) plateaus were taken for all the 74 chambers in the assembly. The Digital-OR signals from the SGS cards connected to the X-strips (X-strips are parallel to the chamber wire) were used to measure the counting rate. For this measurement single tubes were connected in turn to a CAEN high voltage supply and the voltage was varied with a terminal monitor controlling the CAEN system. Measurements were made from a starting value of 3.5KV, in steps of 100 volts, until a current fluctuation was observed on the CAEN high voltage monitor. All plateau measurements were made for SGS card threshold setting of 45 mV. This value is the mid-point of the threshold sensitivity curve.⁸

Fig.II b)7 shows a typical plateau. The main characteristics are the knee at 4.2 KV and a plateau width of about 700 volts. In Fig.II b)8 we show a short plateau 400 volts wide and a long plateau 800 volts wide. The distribution of plateau widths for the entire sample is given in Fig.IIb)9 and has an average value of 613 volts. The knee and breakaway voltage distributions are given in Fig.IIb)10 with mean values of 4.23 KV and 4.9 KV respectively. We find the average counting rate per chamber to be 35 ± 2 Hz, which gives a unit area counting rate of $70 \pm 4 \text{ Hz/m}^2$.

A comparison of the relevant parameters obtained from plateau studies for the Gran Sasso laboratory and sea level values as obtained at SCARF⁹ is shown in Table II.

These data show a shift of the knee of the plateau of about 480 Volts to lower voltage values for the Gran Sasso data as compared to that at sea level. The counting rate at Gran Sasso is lower by a factor of 4 than the SCARF values.

Fig II b) 7

24-A

Fig II b) 9

24-C

Fig II b) 10

24-0

TABLE IIb)II

Comparison of Plateaus at Gran Sasso and at Scarf (Sea Level)

PARAMETERS (Average values)	GRAN SASSO	SCARF ⁹ (Sea Level)
KNEE	4.23+.07 KV	4.710+.051 KV
BREAKAWAY	4.90+.20 KV	5.653+.340 KV
WIDTH	613+113 V	943+311 V
COUNTING RATE	35+2 Hz	140+5 Hz

(b) Portatank Counting Rate

Although the Portatank counting rate could be inferred from the average counting rate obtained from individual chamber plateau measurements, a separate measurement of the Portatank counting rate could provide an additional consistency check. To perform this measurement, the Digital-OR signals from the six SGS cards

connected to the X-strips were ORed together and fed into a scaler. High voltage for both layers was simultaneously varied from 3.8 KV to a maximum value of 4.7 KV. The data taking duration for each voltage value was 60s.

Fig IIb)11 shows the variation of the counting rate as a function of high voltage. The knee of this "Portatank Plateau curve" is at about 4.34 KV, which represents only a 110 volt shift from the average value obtained from the individual chamber plateaus. The measurement was not continued beyond 4.7KV because of small observed current fluctuations. This fluctuation of the current is presumably caused by a few chambers whose breakaway voltages are in the neighborhood of 4.7 KV, as can be seen in Fig.IIb)10. From Fig.IIb)11 we estimate a Portatank counting rate of about 2.4 KHz. This value gives a unit area counting ratio of $65Hz/m^2$, in good agreement with the value $70 \pm 4Hz/m^2$ quoted above.

(c) Operating Point – High Voltage

Information obtained from the measurements described enables us to determine the high voltage operating point for the portatank. Fig.IIb)10 which shows the knee and breakaway distributions obtained from plateau measurements of individual streamer chambers, has a non-overlapping region in the voltage range between 4.5 KV to 4.6 KV. This we believe would be an acceptable region of operation for the entire portatank. For most of the measurements described hereafter, 4.6 KV was chosen as the high voltage operating point. This choice is also consistent with the behavior of the "portatank plateau curve", which shows an onset of noise for high voltage values higher than 4.65 KV. The high voltage between 4.5 and 4.6 KV would shift to a region roughly between 4.9 and 5.0 KV for operation of the chambers at sea level. This is in agreement with the choice of 4.95 KV for the high voltage operating point established

Fig II b) 11

during detailed tests of the streamer chamber and readout system at Northeastern University by some members of the direct mount group.⁸

(d) Hit Distribution of Strip Channels

The channel hit distributions were frequently examined during various test runs of the tracking system. The 452 channels of the tracking system are presented in four histograms, as follows: (see Figs.IIb)12,13).

- i) Horizontal Layer X-Strips (100 Channels)
- ii) Vertical Layer X-Strips (48 channels)
- iii) First Half of Y-Strips (152 channels)
- iv) Second Half of Y-Strips (152 channels)

Since odd numbered SGS cards are connected to LAYER 1 and even ones to LAYER 2, the histograms mix the two layers. The layers may be visually separated by viewing them in groups of 32 (each SGS card has 32 channels). The gaps seen in the channel histograms are due to the presence of unused channels in the SGS cards. The number of TRIGGERS displayed on the top left hand corner of these histograms is the number of events processed by the computer. The computer data-taking rate (about 400 events/s) is lower by a factor of 6 than the portatank counting rate (about 2.4 KHz).

(e) Hit Distribution – Before and After Portatank Rotation

During the gluing procedure the portatank is in the inverted position. To ensure that the portatank orientation does not effect the system performance, channel count distributions for a fixed time duration were examined before and after portatank rotation. These histograms are shown in Fig.IIb)12 (a),(b) and Fig. IIb)13 (a),(b). A comparison of the data before and after rotation shows no dead channels or channels with abnormally high counts, caused by the change of orientation. Both data sets show a uniform response for the 452 readout channels of the portatank.

A comparison of the counting rate of X-strip channels with that of the Y channels, suggests the presence of a greater number of multiple (cluster) hits in Y as compared

BEFORE PORTATANK ROTATION

FIG II b) 12 a)

COUNTS PER CHANNEL, X STRIPS

27-A

BEFORE PORTATANK ROTATION

TRIGGERS : 25073 REAL TRIGGERS : 25073 NULL HITS : 0 TIME : 60 RUN NO : H10002
HISTOGRAM OF NUMBER OF HITS VERSUS STRIP

TRIGGERS : 25073 REAL TRIGGERS : 25073 NULL HITS : 0 TIME : 60 RUN NO : H10002
HISTOGRAM OF NUMBER OF HITS VERSUS STRIP

FIG II b) 12 b)

COUNTS PER CHANNEL, Y STRIPS

27-B

AFTER PORTATANK ROTATION

FIG IIb) 13c)

COUNTS PER CHANNEL, X-STRIPS

27-C

AFTER PORTATANK ROTATION

FIG II b) 13b)

COUNTS PER CHANNEL, Y STRIPS

27-D

to X, since the Y to X ratio does not agree with the expected value of 0.5 based on strip length.

(f) Cluster Distribution

In order to examine the development of multihits as a function of voltage, data were taken (for 60-second duration runs) at ten different high voltage settings on the plateau curve from 4.0 to 4.67 KV. The trigger for the data taking was generated by the OR of all the X strip DIGITAL-OR signals extracted directly from the X strip SGS cards. The event sample for each voltage point exceeded 20,000 events. The data were transferred and analyzed on the Gran Sasso Vax computing facility.

Fig.IIb)14 shows the average weighted MULTIHIT values for the entire portatank (both layers) as a function of high voltage. The X strip multihit curve shows a small increase with voltage, signalling a growth in two-hit clusters. The Y strip multihit curve shows a much more rapid growth. At the chosen operating point of 4.6 KV the Y to X ratio is about 2 (2.57/1.23). This factor of 2 cancels the factor of 0.5 in the counting rate based on the Y to X ratio from strip length, to give the observed 1 to 1 average counting rate that is seen in the channel hit distributions presented in the previous subsection.

Fig.IIb) 15 shows the cluster distribution for the entire portatank at the operating voltage of 4.6 KV.

(g) Y-Strip Performance as a Function of Distance from the SGS Cards

It is of interest to know if the Y-strips have a uniform response, both as a function of the distance along the strip and from strip to strip. In order to study this, we disconnected all tubes from the high voltage manifold, then connected in turn various single tubes and took data, first for a tube close to the SGS cards, then a tube halfway down the Y-strips, and then finally at the far end of the Y-strips. This was done only for layer 1. For each tube, we took data for the same length of time, and each trigger was processed in the standard way by the STROC and the data acquisition system using the PC computer in the standard way. The data show that there is no crosstalk between layer one and layer two, that the response of the Y-strips is uniform along

CLUSTER MULTIPLICITY DISTRIBUTION

FIG IIb) 14

MULTIPLICITY VS. VOLTAGE

Fig II b) 15

the length of the Y-strips, and finally the data are consistent in shape to the data taken when all the tubes are connected to the high voltage.

All the runs with the prototype portatanks tested the readout electronics as well as the mechanical properties of the direct mount method. These electronics tests were clearly very close to actual operating procedures, and are a major advance from the extensive earlier tests in less realistic circumstances which have been described in earlier Progress Reports and in References 5, 8 and 10.

As a final note on recent progress – the Full Boot Node Microvax and the first Tower Microvax, purchased by our group with DOE and Brown University support, have arrived at Gran Sasso and have been installed in Hall A.

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III. ASSOCIATED MATTERS

In February 1990 Asoka DeSilva and David Rossi traveled to Gran Sasso to work on LVD. Dave stayed one month, and Asoka is continuing his stay there through June. They participated in assembling the first LVD tracking system modules, by the direct mount method. They worked on every aspect of this effort, but their special responsibilities were the installation and debugging of the LST readout electronics. In addition, Asoka was responsible for developing the on line data acquisition system for the tests, using an IBM PC compatible Olivetti PC – a faster machine than the Apple IIE we have used in previous tests of the readout electronics. Asoka was also responsible for installing the LST readout and electronics in the second direct mount portatank. Both Dave and Asoka have made and are making outstanding contributions, and we are very proud of them. Mildred Widgoff also made two eight day trips during April and May, mainly to help with the data analysis.

The full Boot Node Microvax II which will control the data acquisition for the whole experiment, plus one tower microvax were both purchased by Brown University (in 1987 and 1989, respectively) using DOE and Brown University funds. Development work on the data acquisition system has been carried out in this country since 1987 but this year the time had come to shift to Gran Sasso. The computers were altered for Italian power requirements and shipped to Gran Sasso, where they are now installed in Hall A of the underground laboratory. Asoka is also responsible for the machine – human interface for the LVD experiment data acquisition.

Unhappily, Professor Shapiro had to leave Italy before the excitement and achievement of the early months of 1990, but he played an important role in liaison with the lab and preparations beforehand. He is working on setting up an arrangement which will allow him to work on computer simulations from his location in Maryland, and his continued participation is very welcome to the project.

Professor Widgoff has been invited to and will attend the Neutrino 90 conference at CERN in June 1990, and the 25th International Conference on High Energy Physics in Singapore in August 1990.

IV. SCIENTIFIC PERSONNEL ASSOCIATED WITH TASK B

A. M. Shapiro – Adjunct Professor of Research(Visiting), Professor Emeritus

M. Widgoff – Professor

Mukunda Aryal – Research Associate

Asoka DeSilva – Graduate Research Assistant

David Rossi - Senior Research Technician

V. PAPERS PUBLISHED AND IN PREPARATION DURING THE PRECEDING YEAR

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